8: Regoliths in 3-D

—John Grant, Andrew Cheng, Allen Delamere, Steven Gorevan, Randy Korotev, David McKay, Harrison Schmitt, and John Zarnecki

8.1. INTRODUCTION

Regoliths are the fragmental, unconsolidated material forming the outer layer of solar system bodies. Because regoliths are an important component of most if not all solar system bodies, they continue to be the target of studies geared toward placing important constraints on a number of fundamental, critical science questions pertaining to body origin and evolution (e.g., *COMPLEX,* 1994). Many measurements that can be made from orbit or from Earth-based observation, such as spectral reflectance and chemical composition, provide information only about the uppermost portions of regolith and not the underlying substrate(s). Thus, an understanding of the formation processes, physical properties, composition, and evolution of planetary regoliths is essential.

We have tried to reproduce the informal character of the discussions held during the workshop and avoid duplication of discussion in alternate chapters in this report (e.g., many of the instruments listed here are cited more completely in Chapter 6). A number of statements are made that are based on the results of prior studies and workshops, but remain incompletely or largely unreferenced. Most references pertinent to these statements can be found in recent National Research Council reports (e.g., *NRC,* 1988, 1990, 1993, 1994, 1995); NASA reports (e.g., *McCord,* 1988; *SSES,* 1994; *OSS,* 1995); summaries of various science working groups (e.g., *MarSWG,* 1991; *LExSWG,* 1992); and LPI (e.g., *Elphic and McKay,* 1992; *Appleby,* 1993), JSC (e.g., *JSC,* 1988), and JPL (e.g., *McCleese et al.,* 1994) technical reports.

8.2. REGOLITH

A planetary regolith is any layer of fragmental, unconsolidated material that may or may not be texturally or compositionally altered relative to underlying substrate and occurs on the outer surface of a solar system body (e.g., *Short,* 1975; *Gary et al.,* 1977). This includes fragmental material from all sources (e.g., volcanic, sedimentary, meteorite infall) and derived by any process (e.g., impact and all other endogenic or exogenic processes). As such, the regolith includes fragmented material whose composition is unaltered from the *in situ* material beneath it; altered by endogenic, exogenic, or *in situ* processes; altered by radiation (e.g., solar or extrasolar); and/or altered by any combination of these or other processes.

Use of this general definition ensures consideration of the near-surface materials on all solar system bodies. For example, on airless, rocky bodies like the Moon, asteroids, and Mercury, the regolith consists largely of rock debris produced by meteoroid bombardment. On Mars and Venus, as on Earth, the interaction of fluids and the atmosphere with the rocky substrate help produce and modify the regolith. For bodies such as comets and the icy satellites, the regolith includes the outermost region of the bodies where interactions with space occur.

8.3. RESTATEMENT OF CRITICAL SCIENCE QUESTIONS

A number of critical science questions regarding solar system bodies in general (e.g., *COMPLEX,* 1994) are easily restated and placed within the context of regolith studies. For example, questions regarding the bulk composition of a body can be phrased as "How does the bulk composition of regolith and its component fragments reflect the bulk composition of the body?" Similarly, questions related to the differentiation of a body and its early thermal state can become "What regolith measurements made in different locations and in different material provide constraints on differentiation of the body?" Questions related to present and past geologic activity and associated thermal and tectonic evolution can be phrased as "What do regolith properties tell us about the geologic evolution of a body and of the ongoing geologic activity on and in the body?"

As the history of the Earth is recorded in the sedimentary record, planetary regoliths contain a history of early and ongoing activity. Because of this potential as "tape recorders" of past events, study of planetary regoliths can help to address questions of the impact history (at all scales) of the solar system and the role of impacts in modifying the surfaces of bodies. On a related topic, regoliths may record and preserve information, helping to resolve questions such as what information the regolith can provide regarding the global stratigraphy and the age of planetary surfaces. Regolith studies can also be used to deconvolve the irradiation history of surfaces due to solar and extrasolar activity and can help resolve questions relating to the history of magnetism of a body.

Questions related to the history of surface-atmosphere interactions and the inventory and location of volatiles on a body can also be restated in terms relevant to regolith studies. For example, what can the regolith tell us regarding the history of surface-atmosphere interactions on a body? Does the regolith provide a significant reservoir for atmosphere and/or internally derived volatiles? Does the regolith record changes in atmosphere and/or internal and/or solar exogenic derived volatiles? If so, how is this information recorded? How does the regolith influence and/or record local/global meteorological events? The potential record of biogenic activity in regoliths requires evaluation of questions such as "What can the regolith record of the distribution and history of biogenic compounds and life on a planetary body?"

8.4. EXAMPLES OF MEASUREMENTS REQUIRED TO ANSWER CRITICAL SCIENCE QUESTIONS

Operationally, studies of regolith samples can be divided into two categories, those involving bulk properties of regolith and those involving individual components of the regolith. For example, some of the critical science questions discussed above could be addressed by determining the chemical composition and mineralogy of bulk samples of regolith fines. However, these and some other questions can also be explored by studying individual particles from the regolith. For example, nearly all the lithologies that were found as rocks (and some that were not) at the Apollo 17 lunar site have been recognized among a random assortment of a few hundred granule-sized (2–4 mm) particles from several scoopfuls of soil (*Jolliff et al.*, 1994). Thus, any of a number of problems that might be addressed by the study of rocks scattered about the surface could also be done by studying numerous small rock fragments in the regolith from a single location. This has proven to be a great advantage for missions with limited mobility (e.g., Luna 16, 20, 24).

The collective character of measurements required to resolve the various science questions will vary widely from body to body as a result of differences in physical properties and state of understanding of those properties. For example, Table 8.1 demonstrates the general kinds of measurements that might be needed to constrain the bulk composition of regolith on solar system bodies given our present state of knowledge regarding their nature. On the Moon, considerable information on regolith bulk composition exists as the result of orbital, surface, and sample return analyses. Hence, the next stage of productive study toward this goal might include a broad spectral survey of the entire surface. By contrast, the properties of mercurian regolith remain poorly constrained and might begin with analyses of as many regolith fragments as possible to evaluate the average composition. On Mars, the next generation of regolith studies might focus on collection of ground truth for existing orbital data and conclusions drawn from the SNC meteorites. Properties of regoliths on cometary bodies are much less well understood, thereby requiring flexibility in evaluation of bulk properties and ensuring the possibility of deep penetration and sampling for pristine materials.

Despite important differences in regoliths and the present state of knowledge about these differences (Table 8.1), a number of general statements can be made about the types of measurements needed to address the critical science questions. It will be important to be able to measure the average crustal composition from orbit to identify variations. If a body is undifferentiated, the orbital measurements should directly constrain bulk composition.

The differentiation history of a body can be constrained through surface or *in situ* measurements of the major- and minor-element composition. Additional constraints on differentiation may be provided by mineral information. Detailed isotopic analysis and age dating will probably require sample return.

TABLE 8.1. Measurements required to resolve critical questions for solar system bodies in varying stages of exploration: Bulk composition as an example.

Body	Present Level of Understanding	Measurements Required
Moon	Bulk composition fairly well constrained by orbital, surface, and sample analyses.	High-resolution broadband spectral survey of whole Moon from orbit and/or surface (e.g., γ-ray).
Mercury	Bulk properties of regolith largely unknown.	Analyze as many fragments as possible to determine average composition. Need major-element ratios relative to an incompatible. Surface patina may be a problem.
Mars	Some information on composition from Viking, Phobos, SNCs.	Need ground truth for orbital data and SNCs. Need composition data from more sites distributed globally. Need to constrain chemistry of dust and analyze volatiles in regolith.
Venus	Some information from Venera, but bulk properties of regolith remain largely unknown.	Analyze as many fragments as possible to determine average composition. Need major-element ratios relative to an incompatible. Need to be concerned with weathering effects.
Outer satellites	Bulk properties of regolith largely unknown.	Analyze as many fragments as possible to determine average composition. Possibly vaporize ice to get gases to constrain composition.
Asteroids	Bulk properties of regolith largely unknown.	Need to get fundamental elemental information (γ-ray?). Trace elements not as critical as majors—want to know if chondritic composition. Might be done best from orbit.
Comets	Bulk properties of regolith largely unknown.	Need fundamental composition data. Should be concerned about sampling sample pristine vs. altered materials. Pristine materials may require deep penetration.

To evaluate the volatile inventory and history of a body, an understanding of the textural properties of regolith (e.g., crystalline texture, clasts, bulk rock, vesicles, etc.) also becomes necessary. The distribution of these volatiles and textures vertically and horizontally within the regolith and within the more general stratigraphic framework of the body is also important. Finally, it would be useful to constrain the heat capacity, conductivity, and thermal inertia of the regolith as an indicator of geologic activity and evolution.

The changing role of impact processes and the overall history of impacts on a body can be inferred from the texture, composition, distribution, and stratigraphy of the regolith. Additional information on the history of impact processes on a body as well as throughout broader portions of the solar system can be gleaned from regolith studies of cosmic-ray-exposure ages, distribution of fission tracks, and chemical and isotopic signatures of micrometeorites.

In order to understand the history of surface-atmosphere interactions on a planetary body it will be necessary to collect data at both local and regional scales. Measurements should target reservoirs of trapped gases and volatiles (e.g., water, CO_2) and must be coupled with chemical, isotopic, and mineralogic information from the regolith (e.g., presence of carbonates) as well as the distribution (grain size, lateral, and vertical) and stratigraphy of atmospherically altered materials.

Exploration of the history of biogenic activity on a planetary body would include a search for microfossils. Such a search should be accompanied by evaluation of regolith stratigraphy (to constrain geologic setting and the history of any life) and an understanding of where water, carbonate, silica, and clays may occur. Useful instruments for these investigations would include a gas chromatograph and mass spectrometer (needed to measure organic molecules). Studies should also emphasize mapping the occurrence of potential ecosystems in the regolith (both with depth and laterally) and might measure the optical chirality. Information on physical properties of regoliths is also required (e.g., yield strength, etc.), especially with respect to sampling effectiveness (see below).

The preceding discussion serves to provide a general sense of the range of measurements that might be made in the regolith on different bodies. It is also clear from this discussion, however, that the variation in the state of knowledge of regolith properties requires differing arrays of instruments tailored to each body (e.g., Table 8.1). In an attempt to account for such a degree of variability in regolith properties and level of understanding, Table 8.2 presents some specific examples of the science objectives, measurements, goals, and possible instrument arrays for future regolith studies on three solar system bodies of widely varying characteristics. This includes bodies for which the regolith properties are largely unknown (comets), to somewhat constrained (Mars), to fairly well understood on a regional scale (the Moon). In Table 8.2,

TABLE 8.2. Specific examples of science objectives, measurements, goals, and instrument arrays for regolith on different solar system bodies.

Comets	
Basic Science via Regolith (Questions)	
	Composition
	Dust and relation of gas to regolith
	Composition as a function of depth
Pristine vs. Altered Material	
	Bigger chunks
	Extrasolar grains
Regolith Science (Questions)	
	Bearing strength
	Physical/mechanical properties
	Porosity as a function of depth
	Bulk density as a function of depth
	Temperature and thermal conductivity profile
	Radar and optical properties
Regolith as a Tape Recorder (Questions)	
	How many Sun encounters ("tree rings")
	Micrometeorite reworking vs. solar processing
	Layered structure
	Interaction with supernova products
Instruments and Sampling Strategies	
	Regolith probe sensitivity to low-density materials
	Incorporating penetrator
	Thermal probes
	XRF
	Mass Spectrometer
	Imager
Mars	
Basic Science via Regolith (Questions)	
	How much water
	Biogenic activity
	Bulk composition/differentiation (as constrained by orbital data)
	Endogenic activity
	Role of impacts
	Volatile distribution between regolith and atmosphere
Regolith Science (Questions)	
	Sedimentary stratification (carbonates, peds., process strat.)
	Dust composition
	Dust vs. other particles in regolith (e.g., volcanic)
	Duricrust origins and distributions
	Atmosphere-surface interactions
	How much water/CO_2/etc. in regolith vs. alternate sinks
Regolith as Tape Recorder (Questions)	
	History of water inventory
	Effects of orbital variations (e.g., layered terrains)
	Atmospheric evolution
	Impact history
	Dust variations (composition, dust storm activity)
	History of endogenic processes
Sampling Strategy	
	3-D sampling of targeted areas—to meters depth
	Sampling above and below dust (if possible)
	Find water and life
	Short-range remote data
	Mobility an issue
Instruments	
	Image of sampling site (from orbit, panorama)
	Image of atmosphere and dust (loading)
	Coring, trenching, penetrators, drills
	Ground-penetrating radar
	Evolved Gas Analyzer (for water and others)
	DSC (scanning calorimeter), Mössbauer, Mass Spectrometer
	Laser Raman
	Microscopic viewer for fossils, other analyses
	IR sensor—locating lithologies favorable for bios?
	XRF/XRD, APX, Laser Mass Spectrometer, Gamma-Ray Spectrometer

TABLE 8.2. (continued).

Moon
Basic Science via Regolith (Questions)
Impact history of the Moon
History of basin-forming events
Basaltic volcanism
Pyroclastic volcanism
Ground truth for orbital data
Use regolith to provide context for analyses of rocks
Regolith Science (Questions)
Stratigraphy and evolution of regoliths on atmosphereless bodies
Space weathering
Small-scale impact events and agglutinates
Mechanical and thermal properties of the regolith
Grain size variations
Nature and evolution of megaregolith
Regolith as Tape Recorder (Questions)
Variations of solar radiation over time
Changes in micrometeorite flux and composition with time
Identify marker beds for impacts on Moon/Earth
Identify marker beds from endigenous events
Effects of supernovae
Sampling Strategy
Number of samples of bulk soil vs. rock chips
3-D mapping and sampling
Drilling
Trenching
Near-surface remote data (GPR)
In situ analyses vs. transportation of samples
Instruments
Innovative drilling and trenching technology
Ground-penetrating radar
Trench and/or borehole mapper
2-D array for mapping vertical/horizontal variations in major-element chemistry, phases, grain size, maturity
Hyperspectral imaging
XRF/APX
Mössbauer

science objectives, necessary measurements, and goals can relate to questions of overall body evolution, specific issues of regolith evolution, or the ability of regolith to serve as a tape recorder. Nevertheless, corresponding sampling strategy and instruments required to resolve these questions will vary significantly with the individual body characteristics and state of knowledge.

8.5. STRATEGIES AND METHODS TO SAMPLE REGOLITHS

Given the range of measurement requirements, possible instrument arrays, and uncertainty regarding the physical properties of many regoliths (e.g., comets), the ability to ensure successful sampling becomes critical and requires inclusion of highly flexible, multimission access strategies and methods. Sample acquisition is needed for some analytical instruments and in the future this technology will be needed for sample return missions from planetary surfaces. If for no other reason, we need good knowledge of regoliths because sample return is listed as a high-priority mission class in the future.

At present, scientific interest and practical technology are converging to drive the development of a new generation of planetary body surface and subsurface sample acquisition systems. Some of the developments of these "present" systems (in addition to the necessary low mass, low power, and full autonomy attributes) are described as follows. First, small samples (probably <1 cc per drill cycle) can be acquired at different depths (usually between the surface and 1 m below the surface). The samples can be sealed at depth to prevent vertical mixing, assure the sample is retained, and contain volatile regolith constituents. Second, sample acquisition systems can be built that are co-engineered with the electromechanical elements necessary to accomplish the reliable transfer (or interfacing) of the acquired sample to instruments located on landers or rovers (or to sample-return holding locations). Third, sample acquisition systems can be made "flexible" to address both task-oriented uncertainties and a cost-constrained planetary exploration environment.

Sample acquisition systems with autonomously selectable multiple modes of penetration approaches can be built to allow for the high probability that samples can be acquired from below the surface of bodies that do not yet have a well-defined surface and near-surface composition. Sample acquisition and sample-to-instrument transfer engineering can also be developed that will be applicable to multiple bodies. A sample acquisition and transfer system can, for instance, penetrate and acquire samples from below the surface of a comet and, with modest reconfiguration, the same basic sample acquisition and sample-to-instrument design can accomplish a similar function within martian regolith. Still other sample acquisition systems can be built with modular instrument integration connections. Through a standard or near-standard interface, sample acquisition systems can serve numerous instruments per mission, accommodate changing manifests, and ease planning concerns for follow-up or related missions. Finally, orbiter sensing allows for the selection of sample acquisition sites of great interest and allows for site selections possessing a high probability of matching sample acquisition to technological capability. Advance knowledge of the surface or near-surface conditions may allow prelanding control modification to best meet sample acquisition objectives.

Drilling (or augering) is gaining acceptance as a means of regolith penetration. While limitations due to mass and power may prevent practical autonomous planetary drilling into very hard rock, many planetary surface regoliths are accessible by novel multiple-mode drilling, augering, and/or percussive drilling. Low-speed drilling (less than 40 rpm) can be effective and is desired to minimize sample disturbance. However, acceptance of drilling or augering as a means of penetration does require acceptance of local mixing of the sample before it is acquired.

Samples can be acquired with sample acquisition cavities opened and exposed to regolith on command, while continued drilling fills the cavities with solid phase material. The cavities are then sealed and the sample is transported to the surface by lead screws or even tethers. Samples may possibly be transported up auger flights and coring, if necessary, and may be workable if performed incrementally with small cores lifted to the surface for analysis.

In addition to drilling/augering-based sample acquisition, consideration is also being given to pyrotechnic and other stored-energy means of penetration. Pyrotechnic sampling offers many advantages: low cost, low mass, simplicity, and excellent penetration potential for hard rock and difficult-to-penetrate regoliths. The limitations of pyrotechnic and similar stored-energy systems are the lack of control over sample acquisition depth and the fact that the amount(s) of sample acquired may be quite small and/or may be limited to a single cycle. Even if the limitations of pyrotechnic or spring-launched-based samplers are eclipsed by capable drilling systems, the pyrotechnic systems, with their potential for extremely low mass and cost-effectiveness, may find a continuing role as a backup means of sample acquisition. Miniature pile driving is another planetary body penetration technique under consideration. With sample acquisition cavities that can be opened and closed on command, pile driving systems may offer coring benefits (no local mixing), may be even simpler than pyrotechnic devices, and may be reusable. A possible disadvantage to pile driving is effectiveness vs. small size when trying to penetrate difficult regolith situations. More study of pile driving systems is desirable.

Application of terrestrial drilling and excavation techniques to planetary settings is often useful, but not without technical difficulty. The electromechanical and control elements of emerging planetary sample acquisition and sample transfer systems are resulting in clever new devices. The current generation of planetary sample acquisition and transfer mechanisms require miniaturization, must posses a very low mass, and must use very low power. These systems are constrained with respect to penetration torque and thrust reactions and require that all sample acquisition and transfer operations be autonomous. Such requirements, taken as a group, are the chief reason why existing terrestrial regolith drilling and penetration technologies are transferable only in a very narrow sense to planetary applications. On the Earth, even for portable drilling systems, there are (almost always) no obstacles to providing drilling operations with large drilling force and drilling torque reaction masses. Terrestrial powered hand drills or augers (as well as the manually operated Apollo drill) leverage sophisticated human control so as to instantly perform complex adjustments in thrust, torque reaction, feed rate jamming prevention, etc., as changing penetration conditions are encountered. Classical terrestrial coring technology is particularly troublesome to transfer to planetary operations. Meter-long cores (for instance) are difficult for precise autonomous manipulations, particularly with respect to instrument transfer or interface operations. Classical coring is also uncertain with respect to bringing an intact core to the surface; unconsolidated material is often lost and cores with bottom "covers" either partially lose material or require failure-prone, overly mechanistic means to achieve retention.

In the future, technology for regolith investigations in three dimensions will need to converge with mature knowledge of the target regolith. Today, a small sample analyzed from a comet is appropriate, whereas for lunar science, scientific interests seek to expose large regolith structure and stratigraphy to analyses. For more information to be gained from targets such as lunar regolith, innovative approaches will have to be put forward. For example, on a lunar rover mission, it should be possible to recover a sample of regolith and analyze it on board as the rover travels to another location (*Korotev et al.*, 1995); this may not be possible with rocks. A scoop in combination with a simple sieve mechanism (a single 1- or 2-mm mesh) would serve two purposes: (1) providing fines devoid of large "clasts" for bulk compositional analysis and (2) a source of granule- or gravel-sized particles. High-resolution imaging of the particles would provide valuable information about the components of the regolith. Another possibility would be to map large cross sections of regolith (1 m × 1 m or larger) with continuous wall penetration or trenching systems combined with instrumentation or sensors that go down into the excavation (instead of transporting small samples to the instruments located on the surface). Loss of definition from this trenching approach may be offset in the future by advances in sensor or instrumentation miniaturization. These efforts might be accompanied by remote evaluation of the shallow subsurface adjacent to excavations using an instrument like a ground-penetrating radar (*Grant and Schultz*, 1994).

8.6. INSTRUMENTATION AND TECHNOLOGIES—EXAMPLES

On different planetary surfaces, the measurements to be undertaken during investigation of regoliths will generally evolve in a logical sequence as exploration proceeds from one phase to the next. Such studies will typically begin with investigations of global issues and then move on to more detailed studies of local issues that may yield regional to global implications. A form of this phased approach to exploration was employed successfully during the Apollo program where remote sensing, Lunar Orbiter, and Surveyor data were followed by the series of manned landings. An additional example of how this phased approach might apply to investigations of regoliths on different solar system bodies follows.

Evaluation of regolith on Mercury would probably begin with a reconnaissance study, whereas the Viking results and analyses of SNCs permit a more comprehensive survey study on Mars. By contrast, on the Moon, analytical studies would serve as a capstone for understanding regolith properties and evolution on a global scale. Goals of each step in this process might overlap in some investigations of other bodies. In other studies, some steps might be skipped. Such decisions would be based on assessment of the difficulty or simplicity of goals, or by occurrence of analog regoliths. A resultant strategy of considering measurements and goals can be developed for any body and will consist of logical sequences of investigations for scientific studies of solar system regoliths. Table 8.3 lists a particular sequence of measurements that is not necessarily appropriate for any specific body, but serves to illustrate the concept.

Choices of instruments selected for a mission will depend on the measurement accuracies required to address specific science objectives at the body in question, as well as available resources for the mission and the environmental characteristics of the body. Relevant mission resources include weight, volume, and power; data storage, processing, and transmission rates; degree of mobility; and sample acquisition, storage, and manipulation capability. Relevant environmental characteristics include atmospheric density, ambient temperature, and surface gravity. As noted in Table 8.3, some instruments can operate in air or in a vacuum, but some require a vacuum. Some instruments have specific requirements for placement relative to a target and some impose requirements on sample handling such as placement of a sample within an analysis chamber. Technical issues that are universal—such as weight and power—are not specifically called out in Table 8.3 unless an instrument imposes unusual requirements. Table 8.3 is not intended to be exhaustive, but merely an illustration of the scientific and technical considerations.

TABLE 8.3. Mission phases and examples of possible instruments.

Phase	Instrument	Comments, Key Issues, Questions
Reconnaissance	Orbital survey/descent imager	Multispectral? Polarization? Stereo?
	Stereo panoramic imager	Zoom? Active focusing?
	Microscopic imager	Multispectral? Polarization? Focusing?
	Sampler for grab samples	Cores
Survey	Physical properties investigation	Sample handling?
	Gamma-ray densitometer/ spectrometer	Emplacement or sample handling?
	Neutron activation	Operates in atmosphere
	Heat flow experiment	Emplacement or sample handling
	Laser ablation/TOF mass spectrometer	Vacuum, sample handling
	Alpha-proton-X-ray	Placement close to sample
	X-ray diffraction/fluorescence	Vacuum? Sample handling
	Laser Raman spectroscopy	Sample handling or placement
	Mössbauer spectroscopy	Sample handling or placement
	Thermal emission spectroscopy	
	Thermal analyses	Sample handling or placement
	Mass spectrometer	Several types require vacuum
	Evolved gas analyzer	Sample handling
Analytical	3-D regolith investigation	Trenching and analyses, high power context, may require ground truth (e.g., seismic), emplacement data
	Ground penetrating radar	
	High-density global network	

* Sensitivity, accuracy, precision, and calibration of each instrument is highly dependent on the science goals of the mission and the nature of the target body (e.g., Moon vs. comet).

Table 8.4 shows, for the same investigation types listed in Table 8.3, our estimate of the level of technical maturity. In some cases, investigations are rated at a low level of maturity simply owing to a lack of development, even though no specific technical difficulties are expected (e.g., microscopic imager). In other cases (e.g., sample acquisition and handling systems), investigations are rated as having flight heritage, even though considerable development may be required for accommodation on a specific future mission because of miniaturization or other technical requirements that would not be met by previously flown versions.

Table 8.5 gives examples of design considerations relevant to a particular investigation type (imaging) with a long flight history, emphasizing aspects peculiar to regolith investigations. Examples of imaging instruments that might accompany each stage of a phased investigation include a relatively simple device at the reconnaissance phase that could be used to constrain knowledge of the regolith environment and determine whether regolith exists and what its mechanical properties are (e.g., of a cometary surface). Such an imager could also be used in support of experiments for determining bulk chemistry. At the more advanced survey stage a multispectral imager might be used to further constrain bulk chemistry and would result in the ability to make

TABLE 8.4. Mission phases and instruments: Maturity.

Phase	Instrument*	Maturity
Reconnaissance	Orbital survey/descent imager	Flight
	Stereo panoramic imager	Flight
	Microscopic imager	Commercial/terrestrial
	Sampler for grab samples	Brassboard/breadboard
Survey	Physical properties investigation	Flight
	Gamma-ray densitometer/spectrometer	Flight
	Neutron activation	Commercial/terrestrial
	Heat flow experiment	Flight
	Laser ablation/TOF mass spectrometer	Flight
	Alpha-proton-X-ray	Flight
	X-ray diffraction/fluorescence	Commercial/terrestrial
	Laser Raman spectroscopy	Commerical/terrestrial
	Mössbauer spectroscopy	Brassboard/breadboard
	Thermal emission spectrometer	Flight
	Thermal analyses	Commercial/terrestrial
	Mass spectrometer	Flight
	Evolved gas analyzer	Flight
Analytical	3-D regolith investigation	Concept
	Ground-penetrating radar	Commercial/terrestrial
	High-density global network	Brassboard/breadboard

* Sensitivity, accuracy, precision, and calibration of each instrument is highly dependent on the science goals of the mission and the nature of the target body (e.g., Moon vs. comet).

TABLE 8.5. Issues related to instruments at each mission phase: Imagers as an example.

Imager	IFOV—resolution
	Depth of view—Active focusing?
	Field of view
	Stereo coverage
	Radiometric requirements and dynamic range
Multispectral Imager	Wavelength coverage?
	Spectral resolution/bandpass?
	Polarization measurement?
	Detector technology weak in UV and IR
	Active detector cooling required?
Hyperspectral Imager	Data volume?
	Loss image compression?

statements concerning regolith properties and evolution that can be applied over at least a local area. At the capstone analytical phase, a hyperspectral imager would ideally result in solutions to the remaining regolith issues over the entire surface of the body.

Design characteristics of instruments at each phase of a study are also critical. For design of orbital and descent cameras in the reconnaissance phase, it is implied that there is a high interest in high spatial resolution as well as a desire for stereo imaging to provide information about the third dimension. Polarization measurements are also desirable to constrain regolith textures. For panoramic and microscopic imagers in the survey or analytical phases, depth of field becomes an additional consideration that may or may not drive requirement of an active focusing mechanism. Wavelength range, spectral coverage, and spectral resolution become issues, particularly in the later phases where we envision the possibility of hyperspectral imaging on very small, possibly microscopic scales; nevertheless, large data volumes will result. Finally, coverage of mid- to far-IR wavelengths may require active cooling of instruments.

Table 8.6 lists technical and environmental issues of particular relevance for regolith studies, leaving aside universally important considerations like power or ambient pressure and temperature. Mechanical properties of regolith are essentially unknown for all bodies except for the Moon and, to some extent, Mars. Properties such as bearing strength and cohesiveness are of scientific as well as operational importance because of implications for mobility and sampling. Transport of fine regolith particles, whether as eolian dust, collisional ejecta, or electrostatically levitated dust on airless bodies, is likewise scientifically and operationally important. The likelihood that abrasive particles will be deposited on spacecraft mechanisms, optical surfaces, or sensitive sensors and electronic components is an additional important design consideration.

TABLE 8.6. Technical and environmental issues.

Microgravity	How to deal with reaction forces from sampling, drilling, emplacement operations
Atmosphere	Winds and eolian dust if present; operation in vacuum otherwise
Mechanical and distribution properties of regolith	Bearing strength, penetration resistance, cohesive strength
Abrasiveness/cohesiveness of regolith	Lifetime, reliability of mechanisms
Mobility of lander	How far over terrain with what relief?
Sample acquisition	From where, how deep, how strong is material to be sampled, preservation of stratigraphy, texture, physical phase?
Emplacement of instruments	How accurate, is thermal/mechanical contact critical, depth

Relative accuracies of the instruments described at each phase of study are dependent on what information is required to address pertinent questions related to the regolith. Accuracy and instrument capabilities at each phase of a mission also becomes dependent on how the instrument is deployed (e.g., in contact with surface or not) and what the results of the preceding phases of the study are.

8.7. SUMMARY AND RECOMMENDATIONS

Science objectives and measurement goals for regoliths can be stated in terms of a variety of critical science questions related to the exploration of solar system bodies (e.g., *COMPLEX,* 1994). Such objectives and measurement goals need to be distinguished, however, on the basis of whether they will contribute to a better understanding of overall body evolution, specific issues of regolith development, the ability of regolith to serve as a "tape recorder" of endogenic and exogenic processes, or a combination thereof. Because regolith properties are largely unknown for many bodies it is important to assure the success of sampling devices in order to achieve mission goals. Therefore, "smarter" sampling instruments should be developed that can assess regolith properties *in situ* and adjust accordingly. A sampler might begin with a simple push into the regolith and evolve into rotary drilling, percussion, and finally pile driving. Given the highly variable state of knowledge regarding the existence and character of regoliths on solar system bodies and the fundamental observation that regolith properties and settings will vary considerably, a flexible, phased approach toward investigations is suggested. For example, an initial stage might presently require a reconnaissance phase at some bodies (e.g., Mercury), a survey phase at others (e.g., Mars, based on the results of Viking and analyses of the SNCs), and a capstone analytical phase at others (e.g., the Moon). Although general statements can be made regarding measurement requirements in the context of resolving critical science questions, variable physical properties and levels of understanding of regoliths require assemblage of differing instrument arrays for differing bodies. Finally, investigation of the subsurface properties of regoliths is crucial and provides critical context for interpreting data from instruments investigating surface properties. Suggested methods of accomplishing this are varied, but include the deployment of ground-penetrating radar and a regolith trenching/sampling device.

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